MIT LIBRARIES DUPL
3 9080 00666020 0

MASSACHUSETTS
INSTITUTE OF TECHNOLOGY

HD28
.M414
no. 3242-
91

DEWEY

MAR 20 1991

WORKING PAPER
ALFRED P. SLOAN SCHOOL OF MANAGEMENT

Technological "Spin-off": Strategic Implications from U.S. Experience

Jong-Tsong Chiang

February 1991 WP 3242-91-BPS

MASSACHUSETTS
INSTITUTE OF TECHNOLOGY
50 MEMORIAL DRIVE
CAMBRIDGE, MASSACHUSETTS 02139

Technological "Spin-off": Strategic Implications from U.S. Experience

Jong-Tsong Chiang

February 1991 WP 3242-91-BPS

Dewey
M.I.T. LIBRARIES
MAR 2 0 1991
RECEIVED

Technological "Spin-off": Strategic Implications from U.S. Experience

Abstract

This paper is to seek strategic implications of "spin-off" from mission-oriented, in particular defense-related, technology programs. Because the U.S. has worldly unmatched military technological capabilities and "spin-off" achievements, this paper focuses on the U.S. experience. By comparing a number of "big" cases, such as semiconductors, computers, nuclear power, aircraft and systems technology, this paper identifies three common mechanisms critical to the success of "spin-off" as well as some unfavorable trends and pitfalls. To synthesize, this paper uses several perspectives relating to the basic characteristics of technology and the unique features of mission-oriented programs. The main conclusion is that "spin-off" is not so serendipitous. There are many rules to follow. However, it would not be pragmatic for most other countries to expect significant contribution from "spin-off."

Contents

1. Introduction
2. Institutional Background and Policy Principles
3. Achievements and Impacts of "Spin-Off"
4. Mechanisms and Patterns of "Spin-Off"
   - 4.1. General Rules and "Big" Cases
   - 4.2. Semiconductors
   - 4.3. Computers
   - 4.4. Nuclear Power
   - 4.5. Aircraft
   - 4.6. C3I and Systems Technology
   - 4.7. Crucial Mechanisms
5. Skepticism about "Spin-Off" Rationale
   - 5.1. Diverging Military and Civilian Requirements
   - 5.2. Adverse Influence on Manufacturing Productivity
   - 5.3. Little Incentive to Cost Containment
   - 5.4. Misguidance of Commercial Technological Efforts
   - 5.5. Diminishing Leverage of Mission-Oriented Programs
   - 5.6. Institutionally Rooted Obstacles
6. Synthesis and Implications
   - 6.1. Radical vs. Incremental Technological Change
   - 6.2. General Direction, Functional Technology and Generic Technology
   - 6.3. Systems Technology and Nationally Based Efforts
   - 6.4. Implications of U.S. Experience to Other Countries
   - 6.5. Contrast with Centrally Planned Economies
7. Concluding Remarks

Technological "Spin-off": Strategic Implications from U.S. Experience

1. Introduction

In this paper, "spin-off" refers to the spill-over of government's mission-oriented, mostly defense-related, technology programs to the civilian sector. By this definition, "spin-off" falls beyond the scope of these programs' main missions, and is by and large unplanned explicitly beforehand. So "spin-off" is basically serendipitous; otherwise, this term would not be appropriate, and it would be more desirable to utilize the same resources available for civilian purposes more directly or through other mechanisms.

"Spin-off" has many dimensions. It may provide employment, boost some industries, cultivate technical manpower, enlarge knowledge base, strengthen infrastructure, and benefit civilian technology development. In this paper, the main concern is technological "spin-off" and its patterns or models. It cannot be assumed, however, that technological "spin-off," if any, will be automatically translated into commercial products or processes. There may still be many things to be done on the part of the civilian industry, including meeting the criterion of economic viability defined by the civilian market. The process may be complex and time-consuming. Therefore, the contribution of technological "spin-off" to the civilian or commercial technological innovation is mostly incomplete or indirect.

Unlike "ordinary" fundamental or basic research, mission-oriented programs are guided by specific missions defined by so-called "mission agencies." These agencies, represented by many countries' defense ministries, have operational responsibilities that mandate rather immediate operating goals and make the agencies under constant pressure to produce results in a rather tangible way to justify their existence. So, R&D--including a small fraction in the category of basic research--endorsed by these agencies are normally relevant to their main missions.

Mission-oriented programs also differ from the so-called "diffusion-oriented programs." Mission agencies are the primary end users of the outcomes of their mission-oriented programs. But the organizations responsible for diffusion-oriented programs are not the principal end users of the outcomes of their programs. Instead, their programs are intended to contribute to a large community consisting of numerous potential users. The R&D results thus have to be diffused to, for instance, farmers through agricultural extension network, or small and medium-sized enterprises througn many local technical centers.

Particularly after World War II, many military (and aerospace) technology programs in many countries were highly sophisticated when compared with their civilian counterparts. These programs might even account for a significant portion of the national R&D resources. The opportunity cost was very high. Therefore, it is often expected that, in addition to accomplishing the designated missions, these mission-oriented programs can somehow also contribute to the civilian sector. It is hoped that by "spin-off" the government's costly investment in these mission-oriented programs can more or less be compensated for, though the original missions are primarily political and military.

Because the U.S. has by far the greatest military technological capabilities and an impressive "spin-off" history, its experience may provide important strategic lessons, especially when "spin-off" has become a conscious, albeit implicit, goal in many expensive military (and aerospace) technological endeavors in this country as well as in many other countries. In the following paragraphs, the U.S. institutional context and some fundamental issues about evaluating "spin-off" will be first discussed, followed by the examination of a number of radical innovation or "big" cases with a view to finding the crucial "spin-off" mechanisms. Then the reasons which may shake the "conventional wisdom" about "spin-off" will be elaborated. Finally, a synthesis leading to some strategic implications will be attempted using several perspectives and taking into account different national contexts.

2. Institutional Background and Policy Principles

Without a tradition of explicit industrial policy, implementation under the shield of "national security" is the most, and sometimes the only, "legitimate" tool for the U.S. government to execute similar jobs. In science and technology, the main purpose of government involvement is to overcome market failures--especially low appropriability and capital market imperfections--that cause under-investment in R&D. So the U.S. government traditionally only supports scientific research and academic engineering, mainly through the National Science Foundation (NSF), and well-defined mission-oriented programs, in which government has a strong and direct procurement interest. In the latter category, the defense R&D consumed a lion's share of Federal R&D budget, from four fifths in the 1960s to two thirds in the 1980s.[1] In 1989 this budget totaled $46.3 billion, equal to one third of U.S. national R&D spending $134.2 billion, and five times all the other OECD countries' defense R&D spending $9,3 billion.[2] In the U.S., the mission agencies responsible for defense R&D are the Department of Defense (DOD) and, to a lesser degree, the Department of Energy (DOE) in nuclear weapon-related research and the National Aeronautics and Space Agency (NASA) in aerospace field.

Despite the mainstream of political ideology and R&D activities as mentioned above, DOE, NASA and some other Federal agencies are also assigned the mission to support the civilian sector. Here, "spin-off" is irrelevant, because civilian technology development falls into their direct responsibilities. Examples include the Applied Energy Program of DOE, the Center for Manufacturing Engineering of the National Institute of Standards and Technology (NIST, the institutional successor to the National Bureau of Standards), the substantial funding on generic aeronautical research and testing of NASA, and the constant efforts of diffusing its technology to the health care industry of the National Institutes of Health (NIH). Nevertheless, in relative terms, the R&D resources available for civilian purposes are small, though the contribution of NASA and NIH is quite significant.

Normally, the defense-related R&D has military mission as its explicit focus. This practice was reinforced by the Mansfield Amendment to the defense appropriation in 1969 to restrict DOD's technological activities to those areas directly concerned with military needs. One exception is the Advanced Research Projects Agency (ARPA) set up in 1958 and renamed DARPA, with prefix "Defense," in 1972 within DOD. This agency was an organizational response to the Soviet Sputnik and cut across the traditional jurisdictions of the armed services. DARPA underwrites long-term and advanced R&D, including basic research and generic technology development, and thus functions more broadly. But its budget is still relatively modest as compared with that under the Services' control, and was only about one fifth of DOD's funding for technology base programs--excluding the Strategic Defense Initiative (SDI),[3] and one thirtieth of DOD's total funding for RDT&E (Research, Development, Testing and Evaluation) in recent years.[4] So, on the whole, the defense R&D investment is indirectly or marginally relevant to the civilian technology and industry. The exploitation of defense R&D results for civilian applications is generally considered to be a matter of the private sector.

Nevertheless, due to the U.S. industry's declining international competitiveness, the Federal government has become more active in promoting technology transfer from defense-related programs to the civilian sector, exemplified by the passage of several laws.[5] Besides, DOD has also got involved in some explicitly civilian programs, for instance, the Semiconductor Manufacturing and Materials Research Consortium (SEMATECH)--an initiative of the civilian Semiconductor Industry Association, and the high-definition television (HDTV) research.

3. Achievements and Impacts of "Spin-Off"

During the three decades following World War II, the U.S. "spin-off" achievements of a number of mission-oriented programs were very impressive. Well-known examples include jet engines (for high-performance fighters and bombers), computers (for plotting missile trajectories), semiconductors (for missile guidance systems),

numerical control (for carving out aircraft structural parts), nuclear energy (for naval nuclear propulsion), lasers (for tank range finders and beam weapons), and time sharing, digital communications and computer graphics (for air defense system).

However, it is very difficult to measure rather accurately the "spin-off" impacts, even only in economic terms. Generally speaking, military R&D may reduce the cost or increase the capability for performing civilian R&D by sharing very expensive equipment, like large wind tunnels or supercomputers, with civilian research, by introducing highly sophisticated military instrumentation to civilian labs, or by accelerating learning experience in R&D through military projects. But the magnitude of influence is not easy to determine. Additionally, many issues involved are also concerned with the fundamental difficulties in assessing technological innovation. For example, let alone the "second order" of contribution, it may be easy to take account of cost saving or price increase resulting from incremental process innovation, but it is difficult to assess product innovation, some of which may be so radical as to lead to new industries. In this regard, U.S. modern military R&D mostly puts far more emphasis on performance than on cost, and tends to contribute more to product than to process innovation. Therefore, the benefits of "spin-off" are normally very difficult to measure.

If the opportunity cost is taken into account, the challenge becomes even insurmountable. Except that there are resources idle and rather readily available, the possibility of diversion or "draining" of limited resources exists. For example, the defense technology programs could be compared with R&D sponsored by NSF, by other Federal agencies, or by commercial companies. They could also be assessed against a system differently managed. And there could even be investments of different weights along the spectrum of basic research, applied research, development, engineering, testing and validation. In fact, many standards and criteria could be used.[6] Though without accurate measurement, in the U.S., given the very large share of national R&D resources consumed by military R&D, the opportunity cost must be very high. Certainly, it could be argued that the consideration of "spin-off" cost is inappropriate because the

cost should be charged against the targeted missions. But when "spin-off" is advocated as one reason to justify part of the investment or as an implicit strategy to bolster civilian technology which has to emphasize cost/effectiveness, the concern about cost makes some sense.

Regardless of the measurement difficulties as noted above, it is apparent that the impacts of some U.S. "spin-off" cases, most notably semiconductors and computers (or information technology), are extremely far-reaching. They have triggered "technological paradigm" change. That is, they have created a new constellation of basic technological artifacts and heuristics or intellectual principles which dictate the working protocols. Miniaturization, software, data processing, digital communications, CAD/CAM, etc. are all associated with the new paradigm.[7] They have also induced "technology system" change, and brought about a range of technological and innovative activities clustering around them. "Mechatronics," office and factory automation, and the integration of computing and communications are obvious examples. What is more, they have affected not merely one industry or group of industries, but spilled over to the entire economy, including working practices and life styles. That is, they have even caused "techno-economic paradigm" shift, and led the way to a modern "information society."[8]

By any measure, U.S. "spin-off" achievements in the early post-war era were unmatched by any other country. In fact, its "spin-off" contribution is by no means confined to its territory. Many other countries also benefit from U.S. pioneering progress.

4. Mechanisms and Patterns of "Spin-Off"

4.1. General Rules and "Big" Cases

In general, it is reasonable to assume that "spin-off" would be more intense, the more similar the military and civilian technologies, or the more closely interactive the military and civilian concerned communities, all others being equal. On a regular basis, "spin-off" may take place in the form of incremental transfer and diffusion of technology through such mechanisms as personal contact, R&D

cooperation, publications, conferences, workshops, demonstration, technical consultation, technical data provision, and the movement of personnel from mission-oriented programs to the civilian industry.

Additionally, even if the military weapon systems are highly specialized and distinctly different from civilian products, and the defense prime contractors are restricted in the communication of classified information, more "dual use" properties may exist in subsystems, parts, components, materials, capital equipment and relevant technical services, and the vast number of subcontractors working for these businesses may not be so subject to strict security regulations. Technology sharing and transfer at these levels may therefore have more common grounds and less obstacles.

Moreover, "spin-off" may also have to do with the extent to which the private industry is involved in military programs. If most military technological activities are undertaken in the government facilities, technology transfer to the civilian industry would be more difficult than if they are executed by private firms. In this respect, the U.S. does not seem to have a considerable structural disadvantage. After World War II the private industry in this country began to play an increasingly important role in military programs. For example, in 1982 86% of DOD's weapon R&D, production and maintenance work was done in the private industry.[9]

However, it is very doubtful that the general rules and mechanisms as mentioned above can rather satisfactorily explain the U.S. uniqueness in "spin-off," exemplified by many radical innovations. Many other countries may similarly do the regular and incremental "spin-off," and have close cooperation in the military-industrial complex with the private industry as a crucial partner to the military in most technical affairs. Some other countries may also adopt more active and better organized programs to enhance "spin-off," just as NASA has been doing since its inception in 1958. Therefore, it seems highly desirable to examine a number of "big" cases in some fields, such as electronics, aerospace and the like, which consumed a large portion of U.S. defense R&D outlays[10] or were historically crucial to the U.S. technological or industrial leadership.

4.2. Semiconductors

In semiconductors, though DOD and NASA supported relevant research, the most radical technological progress, like transistors in Bell Labs and integrated circuits (ICs) in Texas Instruments and Fairchild, did not take place under their direct sponsorship of R&D contracts. Instead, their assured procurement of high performance products in terms of miniaturization at virtually any prices encouraged many firms to invest their own R&D resources, and some of them achieved breakthroughs. Then DOD and NASA became the early largest customers. Their profound influence on the progress of learning economies could be illustrated dramatically by ICs. When DOD and NASA purchased the total IC output $4 million of the first year 1962, the average unit price was $50. By 1966, the last year they still accounted for slightly more than half of the total market $165 million, the price had been reduced to $5.[11]

Besides their procurement as the critical initial impetus to the new semiconductor industry, DOD and NASA played a vital role in accelerating the following progress. In the case of transistors, right after Bell Labs' demonstrated initial success in 1948, DOD began to fund the military application research of transistor in digital computers, communications and missiles. DOD also supported the diffusion of the new knowledge to industry and research community,[12] financed engineering development in Bell, RCA and Pacific Semiconductor, underwrote manufacturing facilities in Western Electric, GE, Raytheon, RCA and Sylvania, and orchestrated standardization of operating characteristics on a national basis in the following years.[13] In the case of ICs, because its space programs demanded extensive miniaturization and extremely high reliability, NASA instituted the Microelectronics Reliability Program setting criteria for acceptance of products and guiding inspection of production facilities. To help suppliers comply with its very stringent specifications, NASA provided technical assistance to many firms, including major ones such as Motorola, Fairchild and Harris, to improve their processing technology.[14]

It is worth noting, however, that, in addition to promoting the diffusion of new technology, DOD and NASA were willing to buy products from small or "untried" firms in order to boost and maintain competition in the semiconductor industry. This practice encouraged entrepreneurship and "intrapreneurship," and helped rejuvenate an industry which might otherwise be dominated by "slower" established firms. As a result, in the late 1950s the large incumbent companies (which had produced electron tubes and other electronics), such as Western Electric, GE, Sylvania, Westinghouse, RCA, Raytheon, etc., only held one third of the total semiconductor market. The rest of the market was shared by three groups of new entrants: new firms established to produce semiconductors (e.g., Transitron and National Semiconductor), existing firms but initially small before entering the semiconductor market (e.g., Texas Instruments and General Instrument), and large established firms from other industries (e.g., Motorola and Hughes).[15] Certainly, this "industrial metabolism" was also facilitated by the fact that learning economies in the early semiconductor production depended on very deliberate experimentation with crystal preparation, control of impurities contamination, and exploitation of precision equipment at most stages. Therefore, established firms merely based on their large production scale or longer "learning by doing" from less sophisticated, earlier generation products did not always enjoy a significant advantage over new entrants which had strong new technical background and better learning strategy.

4.3. Computers

In computers, before the military contracted R&D to the Moore School of the University of Pennsylvania in loose cooperation with Massachusetts Institute of Technology (MIT) for ballistics research in the mid-1930s, there had been a variety of commercial computing machines for business and public service. But the war triggered the military's huge R&D support, and led to the birth of the first fully electronic computer ENIAC (Electronic Numerical Integrator and Calculator) from the Moore School in 1945. ENIAC was capable of computing at speeds several hundred times faster than the earlier

machines, such as Bell Labs' Relay Computers--using telephone relay devices--built for the armed forces, and IBM's Mark I--an electromechanical calculator--donated to Harvard University. So ENIAC provided a great technological impetus to the computer industry and created a cadre of computer engineers and scientists, including John von Neumann. Then DOD sponsored conferences to diffuse the new technology and financed the development of stored-program computers, one type of which--EDVAC, a joint product by von Neumann and Eckert-Mauchly--became the well-known UNIVAC in 1947. Up to 1950, the R&D of electronic computers was almost entirely underwritten by DOD and, to a much lesser degree, by some other agencies like the Atomic Energy Commission (AEC) and the National Bureau of Standards, because no comparable commercial applications needing computing capabilities for purposes like ballistics calculation, government census, etc. were recognized then. Only in the mid-1950s did private investment begin to soar rapidly, and commercial versions--many of which were less costly with smaller scales and less sophisticated functions--begin to prosper.[16]

It is important to also note that initially the civilian industry lacked the technical knowledge to fully appreciate the potential of computers. But the demonstration of the computer applications in military programs in the 1950s and especially in the highly visible space programs in the 1960s greatly accelerated the acceptance of computers by the business world.[17]

In the following decades, despite the fast growing commercial market, government agencies, in particular DOD, NASA and AEC (which was succeeded by the Energy Research and Development Agency and then DOE), continued to be the major supporter of R&D in key fields such as advanced computer architecture and artificial intelligence. DOD's recent Strategic Computing Program is a good example. Moreover, these agencies usually were also the first purchaser of the highest-performance computers that defined the state of the art.[18] The development of supercomputers presents a classic story. For nuclear research, AEC underwrote Control Data's 6600--the machine that dominated supercomputing throughout the 1960s--by advance payments, software support, and the purchase

by the Livermore Lab of two of the first four computers built.[19] In the 1970s, Cray Research pioneered in this field It also worked closely with DOE's Los Alamos Lab which needed massive computing power to simulate the operation of nuclear weapons and nuclear power plants. The lab paid incurred R&D costs, assigned many experts to study Cray's machines, developed both an operating system and applications software, and suggested design changes to better suit its needs. When Cray was on the verge of bankruptcy in 1976, Los Alamos purchased Cray's first machine to bail it out. By 1989, the lab had bought 14 Cray machines.[20]

In the computer industry, though government's competition-stimulating practice was less pronounced, Control Data established by former Sperry Rand employees in 1957 had nearly all its pre-1960's sales from defense and space agencies. This company in 1965 displaced RCA as the third largest computer manufacturer behind IBM and Sperry Rand. In the 1960s, some computer firms, in particular Sperry Rand and Control Data, also benefited from the purchase by these mission agencies which had a policy to improve these companies' competitive position vis-a-vis IBM--then by far the strongest leader.[21]

4.4. Nuclear Power

Beyond semiconductors and computers, another "big" case in the "spin-off" history is nuclear power. After the war, the Atomic Energy Commission (AEC) was formed in 1946 and charged with developing both military and civilian nuclear technologies. Then a variety of reactor types were developed in the national labs. For submarine propulsion the Navy in 1946 picked up the idea of the pressurized-water reactor (PWR), by virtue of its relative simplicity and compact design, from the Clinton Lab. AEC provided all funds and helped transfer nuclear technology from the military programs and the national labs to the private firms involved in this program. Under this arrangement, Westinghouse set up a lab, closely controlled by the Navy's task force leader Hyman Rickover, to develop PWR. In 1955 the first nuclear-powered submarine Nautilus began its successful operation, with a Westinghouse-developed PWR.

Before finishing this military program, Rickover had also been entrusted by AEC with the construction of a pilot nuclear power plant. Westinghouse again was contracted the task in 1953 to build a 60 MWe PWR plant. In 1957 the pilot plant achieved its design power and continued operating in various roles until finally shut down in 1982. In the meantime, GE, while operating government-owned plutonium-producing reactors, also set up a nuclear research lab under AEC's full auspices, and worked with Rickover to build a sodium-cooled submarine reactor. But GE's reactor proved to be uncompetitive with Westinghouse's PWR. Later on GE got the concept of the boiling-water reactor (BWR) from the Argonne Lab. It went on at its own expense to develop this concept. Thus were born the two reactor types, PWR and BWR, that have come to dominate the world's nuclear power industry. Several other countries like France and the U.K., despite their initial work on other reactor types, finally turned to Westinghouse-designed PWR type. And Westinghouse and GE became the major players in this industry. Analogous to the early history of semiconductors and computers, AEC employed many measures, including subsidies and technology transfer, to help private industry get into this new field. The Power Reactor Demonstration Program initiated in 1955 and continued in various forms until 1962 was an example in this line.[22]

4.5. Aircraft

Unlike semiconductors, computers and even nuclear power, worldly revolutionary or radical innovations, strictly speaking, are difficult to find in the U.S. aircraft industry. Even the initial technological leadership in many critical fields did not always arise in the U.S. But during the whole post-war era this country has been making continuing technological progress in a wide front, and dominating the world commercial aircraft market. Reasons are many.[23] Technologically, one is the legacy of World War II. For instance, 12,731 B-17 bombers were produced for the war.[24] So, the U.S. established an enormous infrastructure of aircraft technology, tooling, and production capabilities, as well as skills in design, development, production, and project management. However, the

role played by military programs after the war is also pivotal. The sources of R&D investment could rather firmly support this argument. From 1945 to 1984, the civilian industry spent $18 billion, dwarfed by the military's $81 billion and the non-military Federal agencies' $9 billion (all in 1972 dollars). Without such a strong support from the military, the outcome may have been quite different. Besides DOD, NASA is the second most important agency. Though its main mission was shifted to space programs, which claimed 94% of its budget from 1958 to 1983, after it succeeded the National Advisory Committee for Aeronautics (NACA) in 1958 as a response to the Soviet Sputnik, NASA still made its expensive test facilities, such as large wind tunnels for aerodynamics research, and crucial test results available to the civilian aircraft industry.[25] Its contribution to the commercial aircraft industry could not be underestimated.

Aircraft is an integration of numerous parts, such as engine, airframe, avionics, etc. In addition to the diverse combinations of all elements which are improved over time, aerodynamics is the critical challenge to aircraft design. In the early years, many civilian aircraft were military derivatives, because they were similar to military transports and bombers. So "spin-off" could be quite direct. After World War II, many new aerodynamic problems were brought into relevance by the emerging jet engine. In this respect, the case of Boeing 707, the U.S. first commercial jet, deserves special attention, because Boeing had no commercial transport market when it embarked on the 707, and it had previously failed four times in its efforts to supply commercial transports. Moreover, in the late 1940s, the U.S. Federal government, unlike its British counterpart, refused to finance the construction of a commercial jetliner prototype, so Boeing, like other commercial aircraft manufacturers, had to use its own funds.

To achieve the full potential for higher speed inherent in the new jet engine, Boeing's new aircraft used swept wings at 35°, and was fundamentally faster than the British Comet with a 20° wing sweep. Many related issues, including stability control, were also solved. This critical design in aerodynamics came largely from

Boeing's extensive utilization of the technologies generated by the post-war jet bomber program. In fact, Boeing--the designer and one of the producers of the B-17 and the B-29 bombers--was responsible for the first jet bomber B-47, partly by digesting and applying the captured German research on swept wing aerodynamics. Then Boeing went on to design the very large B-52 intercontinental bomber and introduced it in 1951. Both the swept wing design in the B-47 and the B-52 and the engine J-57 used for the B-52 were incorporated into Boeing's prototype the 367-80, which was intended to be its first commercial jet and, hopefully, a military refueling tanker as well. Eventually, the 367-80 was chosen by the Air Force in the mid-1950s and designated the KC-135. Concurrently the 707 became the commercial version of the 367-80 with widened cabin to permit six-abreast coach seating. The 707 was a big success. One main reason apparently is the "spin-off" from the bomber programs. Another one is the military's purchase of more than 800 KC-135s, of which 450 were committed before any orders were booked. This huge procurement very significantly shared the development costs and drove down the learning curve. Nevertheless, without military orders, the Douglas Aircraft Co. was also successful in its first commercial jet DC-8 which used 30° swept wings and the same engine J-57, and entered service in the same year 1958 as the 707 did.[26] Therefore, the influence of military procurement was not absolute as the DC-8 shows. But both Boeing and Douglas benefited decisively in their aircraft design from the jet bomber programs.

After the 707 and the DC-8, the aircraft technological advances were basically incremental. Their four-engine configuration was followed by variants of tri-engine and twin-engine designs. Finally, the far more powerful supersize fanjet engine triggered the arrival of the very heavy and long range aircraft, such as Boeing 747, McDonnell Douglas DC-10 and Lockheed L-1011. In fact, Boeing 747, another big commercial success, was an adaptation of its military design in the 1960s, subsidized by DOD but failing in the competition for a heavy military transport which later became the C-5A. And, interestingly, the KC-10--the model for the currently largest purchase of military tankers, is a direct derivative of the DC-10.[27]

In engines, several countries explored the various turbine possibilities during and after World War II, because of the maturing of piston/propeller engine. In the U.S. the first big innovation is Pratt & Whitney's J-57 two-spool engine introduced in 1951 for the B-52 bomber. This design had efficiency about twice that of the former single-spool engine by permitting higher pressure ratios, and was much more controllable and reliable. It was also about one third more efficient than the piston engine. Consequently, after powering the B-52 and the first 5 U.S. fighters to exceed the speed of sound in level flight, the J-57 engine was also used in the 707 (as well as the KC-135) and the DC-8, thus launching the age of commercial jet transports in the U.S. Currently, with few exceptions (e.g., the Rolls-Royce RB-211 which has three spools) all commercial jet engines are twin-spool. So, the J-57 was truly a new "dominant design." Nevertheless, it should be noted that prior to the J-57 program, Pratt & Whitney had built Rolls-Royce designs under license for the U.S. Navy. And this was its only jet experience. Besides, it operated a big turbine lab of its own. Therefore, technology transfer from abroad, the company's strong commitment with its own funds, and the specific military program subsidizing most incurred R&D investment are all critical to the success of this J-57 case.

The next important innovation in the jet engine history is the high by-pass ratio fanjet coupling a fan through a turbine to improve the efficiency. In the U.S. the major impetus came from the Air Force which asked for engines with 2 or 3 times the thrust of existing power plants for its heavy transports in the mid-1960s. For this program, DOD covered 55% of the R&D costs, and NASA and the Federal Aviation Administration (FAA) 13%.[28] The fanjet developed by GE was used in the C-5 transport. And Pratt & Whitney's fanjet was incorporated into Boeing 747. Currently, not only 747, but also 727, 737, 757, 767, DC-9, DC-10 and Lockheed L-1011 are powered by a family of fanjets made by either GE or Pratt & Whitney.[29] Therefore, the commercial engines in the U.S. in reality have been heavily subsidized by DOD, because the power plants developed for military purposes could be used quite directly in the commercial aircraft.[30]

It is also worth noting that during the war the military encouraged the entry of the steam turbine firms GE and Westinghouse into the aircraft piston engine area. After the war GE succeeded in becoming one of the few largest jet engine manufacturers in the world. So the strategy to stimulate industry competition and to assure multiple sourcing was also used here, though small firms were virtually excluded because of the high entry barrier rooted in this capital-intensive and large-scale, complex technology.

In structures, military and commercial R&D in the critical elements--wings, control surfaces, cabin, landing gear--remains closely related. In materials, military and civilian aircraft both require similar lightning protection, corrosion resistance, fatigue resistance, material toughness, high strength-to-weight ratio, etc. Therefore, military R&D in these fields is to a large extent "dual use," despite some specific requirements associated with combat aircraft which need to deal with such issues as higher G-loading and maneuverability, and corrosion and exposure mostly on the ground.[31] Mainly due to this "dual use" character, the U.S. presently leads the world in nearly all aspects of advanced composites.[32]

Therefore, on the whole, many critical technologies for aircraft are highly "dual use," and the U.S. civilian industry has benefited enormously from military (and aerospace) programs through large procurement, R&D contracts, and technology sharing.

4.6. C3I and Systems Technology

Across various technological areas, some mission-oriented programs demand tremendous systems efforts. The general or specific expertise and experience acquired from these programs may contribute to the civilian industry with strong systemic character. A dramatic case, though a little "old," is the birth of the Radio Corporation of America (RCA) in 1919. Because of its experience in consolidating radio technology and industry for military purposes during World War I, the U.S. Navy deeply appreciated the strategic importance of radio to national security and economy. Using its systems integration experience at the national level, after the war

the Navy played a central role in promoting the establishment of an "all-American" coordinated radio industry to replace the then largest American Marconi Co.--which was controlled by the British Marconi Co. set up by the inventor of the wireless telegraphy Guglielmo Marconi. In fact, without the Navy's enthusiastic advocacy and arrangements--including buying out the Marconi interests and resources in the U.S. and pooling patent rights from AT&T, GE and Westinghouse to enable one company to have patents enough to make a system, big companies like GE (the major investor of RCA) and Westinghouse (allied with the International Telegraph Company to get into radio broadcasting business after the formation of RCA) might have continued to adhere to their traditional manufacturing business. So, the U.S. radio communications industry owed the Navy a great debt for its far-sighted and systemic vision and patronage.[33]

From a systems perspective, it is not surprising that the above case falls into the category of C3I--command, control, communications and intelligence, where systems design and integration are pivotal to the ultimate success. In this field, after World War II the Air Force's SAGE (Semi-Automatic Ground Environment) real-time air defense system in the 1950s is particularly important. This huge system teamed MIT, IBM, Burroughs and Bell Labs, and laid many of the foundations for time sharing, digital communications and computer graphics.[34] Besides, the SAGE operating system had over one quarter of a million instructions. The following SACCS (Strategic Air Command Control System) even ran over a million instructions as well as an associated auxiliary message system requiring another 300,000 lines of code. These unprecedented large command and control systems nurtured a large pool of software manpower and contributed greatly to the civilian software industry.[35]

Other relevant examples include COBOL, UNIX, ARPANET and ADA, though the impacts of the last one remain to be seen. COBOL was introduced in the late 1950s. Its development was sponsored by DOD for the management of very complex defense logistics and procurement. It turned out that COBOL became the most used business language.[36] UNIX operating system was first developed by

Bell Labs in the early 1970s. But DARPA financed the research at the University of California at Berkeley to add extensive networking and communications functions to the basic Bell system. DARPA's purpose was to make it possible for the wide array of computer hardware hooked up to its network ARPANET system to communicate easily with one another and run the same applications. Consequently, the Berkeley versions of UNIX were incorporated into the later versions of the commercial AT&T system.[37] As to ARPANET, it pioneered the packet-switched communications technology, and, along with another DARPA's project ALOHA Net, provided models and protocols for the design of local area networks (LANs), including the most widely supported ETHERNET.[38] With respect to ADA, it was a product of DOD's struggle with the "software crisis" exemplified by the myriad incompatible languages in use and the increasingly high operation and maintenance costs. So DOD began to support the development of a single multi-purpose, high-order language ADA in 1974. In 1983 ADA's specifications were frozen into a standard, and its use was mandated in all military mission-critical software systems and, certainly, C3I. In the civilian arena, avionics systems have adopted ADA language. As a part of this more generalized initiative, STARS (Software Technology for Adaptable, Reliable Systems) program also commenced in the early 1980s to develop software production technology, including software tools and methods. It is expected that the results of this program could also be used in the civilian sector.[39]

It is self-evident that the improvements in C3I also contribute to systems engineering and management, a critical field for military and space systems programs. In this field, PERT (Project Evaluation and Review Techniques) is a classic example. It was due to the urgent time pressure on the Navy in 1958 to develop the sophisticated Polaris missile system (solid-fueled, intermediate range ballistic missiles armed with nuclear warheads and fired from submerged submarines) that the management developed PERT to plan and control the whole program. Aside from the successful fulfillment of the Polaris Program, PERT has become an indispensable tool in complex project management and systems engineering.[40]

Though without such a dramatic case as PERT, there is good reason to believe that many other military programs similarly had very tight development timetables. These programs might contribute little in a narrower technical sense, because they had to use what were readily available for urgent purposes. But the "spin-off" of the enhanced capabilities in systems design and integration, albeit difficult to track, might have been quite profound.

Large space systems programs such as Apollo and Space Shuttle are also exemplary. Because their missions mandate extreme accuracy and reliability, these systems programs normally have to be technically conservative to avoid unnecessary uncertainties and risks, and mainly focus on exploiting the existing state-of-the-art rather than attempting to generate significant scientific and technological advances. Nevertheless, these programs demand very advanced systems design, engineering and management to integrate very widely separated, specialized efforts. In this regard, NASA--despite the occasional accidents--employed a very wide variety of methods, such as PERT, simulation analysis, data banks, management information systems, etc., in an almost unprecedented and incomparable manner for its huge space programs. Though most of the techniques used by NASA originated elsewhere, they, however, were further refined, augmented and integrated. Through participation in NASA's programs and the movement of experienced people, many delicate systems technologies have been diffused to aerospace and other industries.[41]

4.7. Crucial Mechanisms

Though the "spin-off" cases examined so far are neither exhaustive nor necessarily representative, they do exhibit a great variety of possibilities. By a simple synthesis, however, three mechanisms seem particularly crucial to the "success" of these "big" cases. The first one is the mission agencies' assured procurement of new and expensive products, which creates the initial markets. The second is these agencies' substantial R&D contracts, subsidies and collaboration in the critical technological areas of potentially commercial relevance, without which these areas may be seriously

under-invested by the civilian industry because of the perceived unaffordably high risks or costs. The third is these agencies' promotion of technology diffusion and industry competition, which expands the industrial base and enhances the "industrial metabolism." Through these three mechanisms, the industrial firms (and research institutions) upgrade their technical capabilities, acquire product design and production experience, and drive down the cost. Then the civilian applications, in the form of improved or new products and processes, new industries, or reinforced infrastructure, thrive. For an overview of the whole process, see Exhibit 1. In fact, this model could also be used to explain incremental "spin-off."

(Exhibit 1)

5. Skepticism about "Spin-Off" Rationale

Despite many impressive "spin-off" cases including some as mentioned above, recently there has been a growing skepticism in the U.S. about the "conventional wisdom" toward "spin-off." This new trend seems to reflect the deep concern over the declining international competitiveness of many of its industries, most notably semiconductors, while defense R&D still accounts for the lion's share of Federal R&D expenditures and attracts considerable portion of the national best scientific and technical talent. Plausible reasons for the recent skepticism are as follows.

5.1. Diverging Military and Civilian Requirements

Firstly, there has been a tendency toward diverging military and civilian requirements in many important fields where significant "spin-off" has taken place before. This will lead to diminishing commercial returns of military technological efforts. Apparent examples include "stealth technology" for military fighters and bombers, and radiation-resistant semiconductors for nuclear weapons. They have few commercial applications. In satellites, for covertness, random-orbit rather than geosynchronous satellites are pursued by the military. But in civilian communications, the reverse

is the norm. In remote sensing, the improvements in resolution pushed by the military has been beyond what the commercial applications could economically justify.[42]

In aviation, civilian aircraft has to emphasize efficiency, environment impact, safety and comforts. In contrast, modern combat aircraft puts priority on speed and maneuverability. So military and civilian needs have become very different, which greatly reduces the commercial benefits of military work on airframes in particular. As a result, airframe companies which design and assemble the final products nowadays fund most of their commercial R&D costs.[43] In fact, the divergence in the aircraft speed is also striking. Despite the first operational combat jet (F-86 "Sabre") to break the sound barrier (though only in a dive) in 1947, so far all aircraft used by civilian airlines are subsonic, except a dozen plus Concorde jets operated by the British and French national airlines under their governments' mandate. The fundamental impediments to the commercial supersonic transport are many. Technologically, many difficulties in such areas as supersonic aerodynamics, power plants, and "fly-by-wire" to control the inherently less stability caused by more sharply swept wings are being overcome gradually. But before the commercial supersonic aircraft could be widely accepted, the problems about the efficiency of fuel consumption, the economy of strengthened structures and lighter materials, the sonic booms, the effects on ozone layer and climate, etc. should also be alleviated. In fact, these negative prospects--in addition to the opposition to allocating large sums of public money to fund commercial product development--led the U.S. Congress to terminate in 1971 the Supersonic Transports (SST) Program which was intended to counter the Anglo-French Concorde program.[44] Given the civilian industry's reluctance until today to make significant investment in this field, many unfavorable conditions still exist. By the same token, the recent advocacy for a commercial "spin-off," the "Orient Express," from the hypersonic (with speeds higher than March 5) National Aerospace Plane program is very premature at best. Even if most technical challenges like those involved in the ramjet or scramjet engine can be coped

with eventually, similar questions in SST Program as well as the new logistic issues entailed by an entirely new fuel system based on either hydrogen or methane (in the case of scramjet) will inevitably come up for the commercial version of hypersonic aircraft.[45]

In computer software, there also exist some disputable fields, despite DOD's tremendous contribution in graphics, time-sharing, networking, and some languages. In small-scale applications, such as personal computer-based programs and office automation, both the civilian and military sectors use packaged commercial off-the-shelf (COTS) software. In large-scale applications, however, defense systems are overwhelmingly custom-built, and design-to-cost is not a priority, whereas commercial systems still use as much COTS as possible for efficiency's sake. So there are two distinct software industries at this level. Furthermore, military software requirements are much more rigid than their commercial counterparts. Once approved and documented they will govern the subsequent software development. Therefore, initial divergence, if any, tends to persist. ADA language, as noted previously, is a good case. Because of its purpose to "do all things for all people," there is considerable debate over its efficiency, complexity and commercial viability. So far, with the exception of civilian avionics systems, ADA has not been widely used for commercial applications.[46]

5.2. Adverse Influence on Manufacturing Productivity

Secondly, most military R&D and highly sophisticated weapon systems contribute little to or even adversely affect manufacturing productivity--now the U.S. industry's serious weakness. The main reason is that most military (and aerospace) programs incessantly pursue performance improvements at the expense of cost efficiency. This tends to result in very costly R&D and expensive designs to be produced, and make most purchases of high-tech weapon systems demand only small volumes.

In jet bombers, for example, the B-47 totaled more than 2,000 units, and the B-52 742 units, whereas the successor B-1 was planned for only 100 units.[47] In fighters, depending on the different missions of specific models, the volumes ordered by the military

varied. But the cost trend is fairly clear, just as that of tanks, ships, missiles, etc. within similar weapon categories. In the 1950s, the cost of designing and testing the first supersonic fighters, F-100, F-102 and F-104 ranged between $55-365 million. In the 1970s, the F-16 development program cost more than $730 million, and the parallel F-18 cost nearly $1 billion. Now the Advanced Tactical Fighter (ATF) program is expected to cost several billion dollars. In terms of unit costs, the F-100 was $2.5 million, and the F-16 $20 million.[48] (All the above values are in 1982 dollars.) Certainly, there is also a chicken-and-egg problem here. The increasing unit costs result partly from the generally decreasing production quantities which retard the progression down the learning curve.

5.3. Little Incentive to Cost Containment

Thirdly, relevant to the above one, the present contracting practice does not encourage cost containment, which is crucial in commercial competition. This fact, however, could not be deduced from the official records exhibiting that the cost-plus-fixed-fee and cost-plus-incentive-fee types have been largely replaced by firm-fixed-price and fixed-price-incentive types. For example, in 1987 the latter two contract types accounted for 66% and 14% of the total military procurement funds respectively. But the reality is that there are still many schemes to accommodate cost overruns. On the industry's side, partly due to the technical and other uncertainties inherent in development work and partly due to the opportunistic motives to get approval, costs are often underestimated at the proposal stage. Usually, after so much political and psychological momentum has been gained that program cancelation becomes difficult, many problems begin to surface. On the military's side, it may want to change its requirements at the later development stages, which incurs additional costs. It also wants to prevent important firms from suffering big loss which may jeopardize their competence in serving the future defense needs. Therefore, the fixed-price contract type is often circumvented. The C-5 heavy transport program is a good case. Lockheed won the paper design competition over Boeing and received a $1.95 billion fixed-price-

incentive contract for a "total package," consisting of development work and the construction of 115 aircraft. But it failed in meeting the initial requirements in product development.[49] To continue the work without extra support might lead Lockheed to bankruptcy. So government renegotiated the contract to bail Lockheed out.[50]

5.4. Misguidance of Commercial Technological Efforts

Fourthly, military programs, even for manufacturing technology, may "mislead" civilian technological efforts. A case in point is numerical control (NC). Though tape control for machine tools had been pioneered in the early this century, the modern NC technology was established primarily by the Air Force's auspices beginning in the late 1940s in R&D, software development, training of technicians and programmers, and purchase of NC machines for defense contractors. These efforts were further fueled by the Korean War and the Cold War in the 1950s and 1960s, and still continued in the present Integrated Computer-Aided Manufacturing (ICAM) Program. Initially, NC was developed for making aircraft and missiles which required complex machining and uniformity. But because the Air Force guaranteed lucrative returns, most industrial and technical efforts were geared to meet the Air Force specifications. Other developments which might have proved more accessible, practical and economical for the metal-working industry as a whole were overlooked or abandoned. In striking contrast, the Japanese companies imported the U.S. technology, standardized NC machine tools, and made them easier to use, more reliable, and less costly for machining simpler shapes of products. As a result, many Japanese firms, like Fujitsu-Fanuc, have been very successful in the world market. On the contrary, the U.S. became a net importer of machine tools in 1978, the first time since last century, and many U.S. manufacturers outside the aerospace industry adopted NC technology via the Japanese. Therefore, it may well be argued that the U.S. Air Force unpurposefully "misled" the civilian technological efforts in NC.[51]

There are some clues that a similar history may repeat in the field of advanced materials. The U.S. present leadership in especially

advanced composite technology of all types is a result of military and, to a lesser degree, space programs which were aimed at such goals as higher operating temperatures, greater toughness, reduced weight, and even lower radar observability. But so far the advanced materials developed for these purposes are expensive, and the fabrication processes are poorly suited for mass production. According to potential U.S. commercial end users, the major use of these materials will not be profitable within the next five years. In many cases, 10 to 20 years will be required to solve the remaining technical problems and to develop rapid, low cost manufacturing methods. Hence, with the exception of civilian aircraft whose requirements are still less stringent than their military counterparts, there is little commercial "market pull" on advanced materials technology. As a consequence, the major military contractors in this field have not played a significant role in the commercial area. Nevertheless, in Japan which has relatively small indigenous military and space R&D and a "fledgling" aircraft industry, most efforts in advanced materials are explicitly commercial. They focus on fine ceramics, carbon fibers, engineering plastics, and amorphous alloys. Many large integrated companies create "market pull" through the applications in their existing products, and maintain "technology push" through long-term investment in gaining production experience. One example is Toyota's diesel engine piston which consists of aluminum locally reinforced with ceramic fibers. In the European arena, many companies are also cooperating even internationally in developing advanced polymer matrix composites for automobile structures.[52] This is a harbinger of the strategy similar to that of Japanese NC--using advanced technology in low cost, high volume commercial applications. In contrast, the U.S. counterparts still mainly emphasize higher performance at the expense of lower cost.[53]

Another somewhat controversial case happened in the early history of transistors. According to Bell Labs' plan, its transistor was to be used in telephone amplifier, radio receiver, circuit oscillator, and other civilian electronic products. But under the military's request (because this company had extensive experience with

complex military projects during World War II), AT&T had to use its then limited technical resources in this new field chiefly for military projects throughout the 1950s. This may partly explain the delay of AT&T's large-scale application of transistors even in its own telephone system until the early 1960s.[54]

In nuclear power, by hindsight, the Navy's and AEC's early dominant influence might not be without serious flaws. PWR type may be literally well suited to submarine propulsion. But to use the Navy's better understood PWR also for the civilian pilot plant created a great momentum. Some other concurrently developed alternative reactor types, which might have otherwise proved at least equally viable if they had been given similar support, hence did not take root in the nuclear energy field. Besides, in contrast with the gas-cooled graphite-moderated reactors (GCRs) which are fuelled by natural uranium and were initially chosen by France and the U.K., PWRs and BWRs have to use uranium consisting of the fissile isotope U-235 enriched from its natural level 0.7% up to about 3%. When nuclear power was first explored in the West, only the U.S. had enrichment capacity principally for nuclear weapons. So, PWR and BWR technology was nurtured in the U.S. and moved down the learning curve much faster than other alternatives. But as the ambitious scaling-up went on from the initial 60 MWe pilot plant to the current 1000 MWe commercial plant, many safety and reliability problems arose, and the treatment of radioactive wastes became an intractable issue. As a result, in recent years a number of institutions and individuals--including the inventor of PWR, pioneers of the nuclear power industry and a former AEC chairman--have started to seek a new path and try different reactor concepts.[55]

5.5. Diminishing Leverage of Mission-Oriented Programs

Fifthly, mission-oriented programs have lost their potential leverage in many fields where procurement or R&D investment has become predominantly commercial. The history of semiconductors reflects this trend. The military bought nearly all the 90,000 transistors, mostly produced by Western Electric, in 1952,[56] but only 47% of transistors and 33% of all semiconductor devices by value in

1963.[57] In 1962 the military and space agencies purchased the entire $4 million of IC output, but in 1967 they were surpassed by the commercial market, and by the end of the 1960s the rapidly growing computer industry had become the largest end user market.[58] Finally in the mid-1980s, DOD accounted for only less than 10% of all semiconductor sales and 3% of the quantity of chips.[59] In the meantime, unlike transistors and early ICs, the great success of the following complementary metal oxide semiconductor (CMOS) and microprocessor technologies, developed by Mostek and Intel respectively, entirely lacked the support from the military--in the form of R&D contract, early purchase of expensive products, or assistance aimed at improving production.[60] In 1980, DOD launched the 9-year Very High Speed Integrated Circuit (VHSIC) Program principally for military purposes. But this program was construed more broadly as also to strengthen the U.S. IC industry. With the initial budget, $200 million, expanded to nearly $1 billion to incorporate the technology into military systems, this program, however, did not cover newly emerging technologies, like gallium arsenide (GaAs) chips (whose development was sponsored by DOD since the 1960s). Its main focus on silicon semiconductors higher speed and density was rather consistent with the mainstream industry efforts, and thus in effect shared the development costs for commercial markets. This is one reason why many firms took part enthusiastically.[61] But the relative importance of this program's potential "spin-off," though yet to be seen, is quite questionable, because its investment is very modest when compared with commercial R&D. Take 1985, about the middle year of VHSIC program, for illustration. The U.S. semiconductor industry--excluding captive firms (with semiconductor production mainly for internal uses and not for sale in the open markets like merchant firms) such as IBM and AT&T--spent $1.8 billion or 18% of the total revenue in R&D.[62] Besides, in this program only the large established systems companies were virtually qualified to participate, given the huge entry barriers in the present semiconductor industry. So the likelihood of "industrial metabolism" which might otherwise be

enhanced by DOD's support for new entrants to challenge the incumbent firms has also diminished.

In computers, a similar pattern exists. By the time when Sperry Rand delivered the first commercial UNIVAC computer to GE in 1955, the annual military market had already reached $200 million. But ever since 1962, the year with total hardware sales $2,300 million, the commercial market has been ahead of the defense and space market with an increasingly wider discrepancy.[63] By 1979 the computers for military use had shrunk to only 3.6 % of U.S. annual production, though the defense build-up in the early 1980s slightly reversed that tide.[64] With respect to R&D investment, in the 1950s government R&D contracts (including the large STRETCH computers) represented about 60% of IBM's total R&D expenditures. Around 1960 the military still funded major computer firms at significant levels, for example, about 80% in Sperry and Control Data, 70% in Burroughs, and 35% in IBM. But the highly successful IBM 1401, 360 and 370 series were completely financed by the company's own funds. In the 1980s less than 10% of the R&D investment came from the military at most major computer firms.[65]

In nuclear power, a similar trend could also be observed. In the early years, government sponsored all R&D of various reactor types in the national labs. Later on utilities, architect engineers and nuclear steam supply system (NSSS) suppliers (e.g., Westinghouse and GE) joined in constructing pilot or small commercial plants, and then developing larger-scale plants as well as tackling many incurred safety and environmental issues. In terms of R&D expenditures, the civilian industry began to significantly surpass AEC (including the Navy's reactors) in 1958.[66]

5.6. Institutionally Rooted Obstacles

Finally, many fundamentally different rules and practices in the military and commercial sectors constitute many barriers that impede "spin-off." Nevertheless, when compared with the unfavorable trends or "pitfalls" as discussed above, the following cited obstacles are more institutionally rooted, more predictable, and even not new issues at all.

First, the restriction of communication of classified information as well as government regulations and procurement practices makes many defense R&D units isolated, psychologically, physically and administratively, from commercial R&D departments. This inhibits technology sharing and diffusion even within a firm's formal organizational boundary.

Second, DOD's principle to separate R&D contracts and production contracts in order to avoid "lock-in" effect extended from R&D to production and encourage competition in both areas hampers the incorporation of manufacturability into the development phase. As a result, the final products, even after adaptation, are normally too expensive for the civilian markets.

Third, DOD's another principle to force its R&D contractors to share DOD sponsored R&D results with DOD specified firms in order to ensure multiple supply sources makes many high-tech firms decline to bid on defense projects for fear of losing their proprietary information and advantage in civilian markets. Therefore, the possibility of "spin-off" through these competent companies--which may otherwise be further strengthened technically by joining military programs--largely decreases.

Relevant to the last point, many companies are also discouraged from taking part in many military programs, because they perceive that the bureaucratic encumbrance, commercial counter-productivity, and budgetary fluctuation are commonly associated with government projects.[67]

6. Synthesis and Implications

In consideration of the above negative prospects of "spin-off," the three crucial mechanisms as pointed out previously are ostensibly not straight "panacea." In this section, several perspectives will be used to synthesize the seemingly very divergent phenomena, and the implications to other countries will also be discussed briefly.

6.1. Radical vs. Incremental Technological Change

By a loose definition, a radical or revolutionary technology is not on the general trajectory of some existing technological paradigms in which the progress is predominantly incremental or evolutionary. Therefore, the progress at the stage of radical or revolutionary change is very difficult, if not impossible, to predict, plan and manage. It is thus not very likely for mission agencies to bet on the "right horse" through direct R&D endorsement. Only after a new and promising technological paradigm emerges could it be more effective for mission agencies to accelerate the progress through further R&D investment, procurement, production support, technology diffusion, etc. As the "theater" becomes predominantly commercial, the mission agencies' overall leverage will diminish. But their influence may remain in the high-end fields which are critical to their missions and still being pursued vigorously.

The history of semiconductors in the U.S. roughly fits this pattern from the outset (when the solid-state physics, on which modern semiconductors are based, was then a newly emerging and highly volatile field) to the recent VHSIC program (with its very limited influence on the development of silicon semiconductors of commercial relevance). Nevertheless, the electronization of computers was already in a more or less predictable trajectory. So DOD's direct, strong R&D endorsement was decisive. As regards jet engines, in particular the 2 innovations--the two-shaft turbojet and the by-pass fanjet, they were largely engineering development, and did not rely on very unpredictable scientific discovery and progress (though a wide array of scientific and technological disciplines as well as learning experience were needed). Hence in a technical sense they were not too radical for DOD to bet. In nuclear power, the pattern is slightly different. Because of the military origin of most basic technologies and the very high military sensitivity of related technologies, government involvement, exemplified by the national labs' work on various reactor concepts and the Navy's influence in the first civilian pilot plant, was much deeper in the genesis of nuclear power. Later on, when the public concern over safety and environmental impacts soared, government's initial promotional role changed into a largely regulatory one. What is more, in both jet

engine and nuclear power, only a small number of established firms had the capabilities to do the large-scale R&D. So it is less likely that DOD would contracted or subsidized "wrong horses."

It is worth noting, however, that at the initial diffusion stage of radical or revolutionary technology, reliance on pure private efforts may not be so desirable from the standpoint of the whole social benefits. On the part of the private inventors, their resources to exploit the new technology may not be sufficient, and their protection of proprietary rights to appropriate economic rewards may slow down the diffusion process. From this point of view, the delay of using transistors in AT&T's own telephone system may have been more than compensated by the earlier industry-wide utilization, mandated by the anti-trust settlement and accelerated by the military applications which helped drive down the unit costs. This is one of the potential advantages inherent in government sponsored R&D and militarily critical innovations, because promoting the exploitation of them is government's legitimate responsibility, though, on the other hand, the diffusion scope may sometimes be restricted for national security's sake.

6.2. General Direction, Functional Technology and Generic Technology

If technological progress is looked upon in terms of more basic elements, then the conceptual distinction between the revolutionary or radical innovation and the evolutionary or incremental innovation as mentioned above may become blurred. For example, it would not be surprising to predict that technology will proceed in the direction of being faster, more powerful, more accurate, more reliable, more accessible, more available, etc.--given the same input, or using less materials, less energy and being physically "lighter, thinner, shorter and smaller"--given the same output or functions. From this perspective, the general direction of technological progress is fairly recognizable, and the R&D endorsement in the right direction is possible. Even if the bet on a specific technical approach, device or machine eventually proves incorrect, the knowledge and infrastructure accumulated may still be relevant and can contribute

significantly to the continuing progress once the "right horse" is identified. Therefore, it could be said that DOD's early investment in the direction of miniaturization, computing power, communication capacity, etc. was generally correct. DOD's long sponsored research on GaAs semiconductors for processing speeds and artificial intelligence for "intelligence" may as well belong to this category.

Nevertheless, it should be cautioned that, because many military programs at their R&D stage prioritize performance and time schedule over cost, manufacturing productivity usually is their weakness. The commercial three-way balance between performance, time and cost must be made by the civilian industry itself. In this sense, how to capitalize on NC and advanced materials technologies generated from military programs for commercial purposes mainly falls upon the civilian industry's shoulders.

Moreover, as the case of nuclear power shows, if a specific core technology, device or machine (e.g., a basic reactor type) necessitates the development of other "complementary" technologies in a very closely integrated manner (e.g., the nuclear steam supply system), then there is a potential danger that the initial momentum created chiefly for military purposes may grow into a "critical mass" difficult to resist or change, and the following efforts may be led into a direction not really optimum to the civilian sector.

To better understand the divergence and convergence of military and commercial technologies, another perspective similar to the last one is instrumental. At the systems level, military and commercial requirements may look very different from each other. But both may consist of many common functional dimensions, despite being weighted differently. It is at this functional level that mission-oriented programs could more definitely contribute to the civilian sector. In consideration of economic viability or systems equilibrium, the commercial applications may not fully utilize the results from military programs. The latter, however, may still define the state-of-the-art of these functional technologies and provide clues for the future commercial efforts. This rationale could be applied quite well to semiconductors, computer architecture, remote sensing and the elements of aircraft such as aerodynamics,

propulsion, structures and materials, but less well to the whole aircraft which is, for instance, one level higher than engine in the systems hierarchy and, accordingly, should be defined more in commercial terms.

The two perspectives of "general direction of technological progress" and "functional technology" as suggested above are slightly different from a currently prevailing perspective of "generic technology." Loosely speaking, "generic technology" means a concept, component or process, or the further investigation of scientific phenomena, that has the potential to be applied to a broad range of products or processes. So it may have the potential of being both militarily and commercially relevant. Examples include the science base for manufacturing, basic technology about structural integrity and combustion process, software tools and methods, etc. Nevertheless, "generic technology," conceptually, is "pre-competitive," covering research activities up to the stage where technical uncertainties are sufficiently identified to permit assessment of commercial potential and prior to development of application-specific prototypes. So, it is basically a stage in the "R&D spectrum" or "innovation pipeline" (which has feedback and feedforward loops linking different R&D stages). The importance of this perspective lies in its inherently novel strategic thinking. First, it turns the attention from the properties of R&D activities (e.g., basic research, applied research and development) to the usage of R&D results--with wide applications and diffusion as a goal. Second, it grasps the essence of the "convergence" of (or the blurred distinction between) modern science and technology, rendering unnecessary the "artificial demarcation" in between.

As regards the two perspectives proposed here, they are constructed in terms of the contribution to the missions. So they do not have the "precompetitive" limitation. They could cover advanced development, production and construction, systems use, and modification. It is evident, however, that these three perspectives are cross-fertilizing. "Generic technology" could be a criterion for organizing technology programs with more "spin-off" potential.

"General direction" and "functional technology" could be a guidance for identifying the "spin-off" opportunities to capitalize on.

6.3. Systems Technology and Nationally Based Efforts

From a systems perspective, because the U.S. has an unmatched high-tech military machine and a global military presence, its C3I could be judged to have no comparison in the civilian sector or even in the whole world in terms of its scale, complexity, speed and many other functions. Therefore, it seems not surprising that there has been a steady flow of contribution from C3I-related programs to the civilian sector. A similar rationale may as well be applied to many large-scale complex mission-oriented systems programs. Though it is usually difficult to track because of few easily recognizable "packaged" technologies, the "spin-off" of systems engineering and management capabilities from these programs may have been widespread and contributed significantly to industries with strong systemic character in particular.

Finally, as compared with their commercial counterparts, mission-oriented technology programs have three rather unique features. First, because national security cannot be judged in commercial terms, relatively long-term commitment to some critical technologies (not necessarily specific products) could be more easily assured. Second, because these programs are mission-focused and usually under big pressure from the military commanding system, concentrating efforts on some mission-critical fields would be a normal strategy. Third, resources may be mobilized on a national basis. Therefore, if the general direction or the specific focus of investment is sound, military programs may be more effective, albeit not necessarily more efficient, in pioneering some critical technological (not scientific) frontiers or attaining designated technological objectives. This may explain U.S. mission agencies' consistently paramount role in C3I and aircraft technology, and particularly strong influence on many worldly state-of-the-art and radical/revolutionary technological fields where the U.S. civilian industry alone could not achieve and no other countries could compete.

6.4. Implications of U.S. Experience to Other Countries

In applying the strategic implications derived from the U.S. experience to other countries, the U.S. uniqueness should first be examined. First, the U.S. has by far the largest defense-related R&D investment and high-performance product procurement in the Western world. Second, this country during the quarter century following World War II was the world's most productive economy by virtually all measures and the technological leader across a very broad front.[68] As a result of the multiplying effect of these two advantages, the U.S. in effect leads all the other countries by a significant edge in both the generation of new technologies from the military programs, and the exploitation of these technologies in the commercial sector--or at least in the fields it maintains leading position.

As a corollary, it may turn out that even similarly advanced "spin-off" in other (advanced) countries may be rendered uncompetitive eventually, because the alternative "spin-off" in the U.S. tends to have better learning economies. The ultimate abandonment of the indigenously-developed nuclear reactor in France and the U.K. is a good illustration.

So, there is little likelihood that really radical innovations would originate from military technology programs in other countries, which almost certainly would lag behind their U.S. counterparts in terms of resources invested and technological levels targeted. As to the unradical innovations of commercial relevance, it is very probable that the civilian industry has already played a dominant role in the U.S. or in some other advanced countries, if not in the countries where the military programs are located. Then it would be very difficult to justify the cost effectiveness of the conscious "spin-off"--noting that there still are many things to be done to meet the commercial criteria, if the option to transfer the technology among commercial firms, even across national borders, exists. Therefore, it does not seem to be pragmatic for most other countries to expect significant contribution from "spin-off."

Among the advanced countries, the above unfavorable prospect of "spin-off" would naturally be more serious for small countries, all others being equal. If these countries pursue self-dependence in some final products, such as combat aircraft, battle tanks, submarines and missiles, they may have to concentrate their much limited technological resources on systems design and integration, and rely heavily on readily available subsystems and functional technologies at home and from abroad, because of the large "threshold investment" required in developing modern high-tech military items. Then "spin-off" may mostly be confined to the systems capabilities. In the meantime, the military may have no slack to deliberately promote "spin-off." In these small countries, to have their own first class weapon systems, albeit much fewer in models for various missions when compared with larger countries, is already too big a challenge.

When the dynamic industrial development is considered in the context of a developing country which is shortening its gap with advanced countries, the above general argument may need some modification. Usually, a "follower" country's domestic capabilities for a military item evolve in the following sequence: maintenance and repair, licensed production and upgrading, independent production of subsystems, and finally independent design and production of whole systems (certainly still relying on other countries for many parts and subsystems). In parallel, the evolution also proceeds in the direction of making more sophisticated weapon systems.

If a model of three stages is applied here, then at the first stage when the civilian industry is underdeveloped, military technology chiefly imported from abroad may help transfer relatively simple technology and management to the local industry, and upgrade industrial infrastructure by training people in uniform maintenance and production--a key element of modern military technology. So, the military industry may play a leading role in demonstrating and diffusing Taylorist production and management. At the second stage, the civilian industry is more developed, and the local content of more complex military products increases. The private industry may now participate in more advanced production, and some large firms may

even become prime contractors working on systems integration and design for some military items. Through these firms, many "dual use" technologies, for example, electronics and systems engineering, could be diffused to the civilian sector. At the third stage, many civilian industries have attained rather high levels of technology and management. The technological capability gap between the two sectors is further shortened. "Spin-off" becomes more difficult. And the general argument as precedingly proposed becomes more relevant.

6.5. Contrast with Centrally Planned Economies

As far as centrally planned economies are concerned, the USSR could be a representative case. This country's huge military investment in terms of procurement and R&D is only matched by the U.S. Its military and aerospace technology is also second to none but the U.S. But there is little evidence that this country has had significant "spin-off," with the exception of aircraft and nuclear power.

In the USSR, the airliners were normally developed by the same organizations, such as the well-known Tupolev and Ilyushin Design Bureaus, that worked also on bombers, military transports and even fighters. Though military projects were traditionally prioritized, many civilian versions derived from their military models achieved remarkable technological records. In the post-war era, the huge turboprop TU-114 entered civilian service in 1957. This family only later was displaced by Boeing 747 as the world's largest, heaviest airliner. In 1956 the TU-104 joined the Aeroflot Airline's fleet. This is the world's first operational jetliner, without peers for two years until the entry of the 707 and the DC-8. Its engine M-109 was the world's largest operating at that time. Its range was also longer than the 707 and the DC-8. The TU-104 provided service until 1980 with good reliability and safety record. This nearly all-Soviet product, like Sputnik, was seen as another proof of the rapid scientific and technical progress in the USSR. It is noteworthy that both the TU-114 and the TU-104 had been developed inexpensively from the military designs, the Bear and the

TU-16 bombers respectively, in only eighteen months. The "spin-off" effect was very high.

However, the strong pursuit of speed, range and capacity, usually at the expense of more economically justifiable designs, also characterized the Soviet civilian aircraft development. There was little profit incentive as a driving force. There was also no "objective" cost accounting system in this country to push aircraft designs in the direction of efficiency. Therefore, despite the high cost consciousness on the designers' part to make economically viable aircraft also for the world market, the hurdles rooted in the counter-productive institutional context proved to be too difficult to completely cross.

The TU-144 program which led to the historic first flight of an supersonic transport on December 31, 1968 also typifies the Soviet-style development. The 25 years' persistent investment pushed the program steadily forward and achieved high technological levels in aerodynamics, fuselage and engines, though its electronics and comforts could not match the Western counterpart Concorde. However, its commercial viability was eventually crippled in its unresolved weakness in range, reliability, efficiency and noise. In 1983 the supersonic fleet of about a dozen and a half units was dropped from the Aeroflot's flight plan after more than 10,000 air-hours. Before this final decision was made, no pragmatic world of civilian aviation had seriously challenged the course of this program as in the U.S., or even in France and the U.K.--despite the continuation of their Concorde program and flight.[69]

In nuclear power technology, the USSR is almost totally self-dependent. Based on the basic technologies originating from the military sector, this country operated the world's first experimental nuclear power plant (with output 5 MWe) in 1954, developed the world's first tokamak (i.e., the magnetic confinement for nuclear fusion) in 1968, and made remarkable progress in the fast breeder reactors. In effect, the excellent technical progress in terms of output scale and new reactor R&D was pushed forward by its long-term commitment, large-scale investment and centralized management. But, on the other hand, the safety factor was largely

neglected, resulting in the unacceptably bad safety designs in all light water-cooled, graphite-moderated reactors (i.e., Chernobyl-type reactors), according to the Western standards, and the world's most disastrous Chernobyl accident in 1986. Had an independent voice outside its centrally controlled system existed and warned against the pitfalls, the very "unbalanced" development might have been avoided. This certainly does not imply that many safety and environmental issues as have been faced in the West would not happen in the USSR.

Modern information technology is another case in point. Many of its advanced military and space systems suggest that the USSR must have possessed some technical capabilities in advanced microelectronics, computers and telecommunications. But this country has failed in creating a viable industrial base comparable to the West. It imitated IBM computers for its RYAD series, but the quality was bad and software support weak. It produced ICs, but the yield rate was low and reliability poor at least in those for non-military uses. Even in microcomputers which do not really demand more advanced and sophisticated technological capabilities than larger computers do, the USSR (as well as the whole East European bloc) entirely lacks the vitality to grasp the dynamically changing opportunities. As a matter of fact, the modern information technology in the USSR has been described as a crisis. This weakness has constituted a serious barrier to the development of many fields, including nuclear power. For example, in 1988 the USSR had only 2 simulators for its 58 reactors, whereas the West has an average of 1 simulator per 3 to 4 reactors.[70]

Therefore, on the whole, "spin-off" has been severely "distorted" or nearly completely stymied in the USSR. This country has a large pool of military and aerospace technology, but its civilian industry is incredibly weak. So, even if its government makes conscious and great efforts to convert military technology for civilian purposes, there is no autonomous, vigorous and market-oriented civilian industry that could actively take advantage of the "spin-off" opportunities according to the commercial rules. Besides, for lack of the "virtuous circle"--in which a strong civilian industry in turn

supports the military sector, the further development of military and aerospace technology in the USSR has also been seriously jeopardized.

7. Concluding Remarks

In addition to some general rules, three mechanisms critical to the success of several "big" cases in the U.S. "spin-off" history are identified in this paper. The first is mission agencies' initial procurement of new and expensive products; the second is their substantial R&D contracts, subsidies and collaboration; and the third is the promotion of technology diffusion and industry competition. However, some trends, practices and pitfalls are also found to inhibit "spin-off": diverging military and civilian requirements, and mission-oriented programs' adverse influence on manufacturing productivity and cost containment, misguidance of commercial technological efforts, and diminishing leverage.

By comparing many phenomena across different cases, this paper suggests that the potential contribution of mission-oriented programs tends to be more crucial when the targeted technology is at the stage of radical change, and confined to the high-end fields when the innovation is predominantly commercial and incremental. In the meantime, the contribution of these programs also tends to be more steady and predictable in some critical "functional technologies" and "general directions of technological progress." Because many C3I and large-scale complex systems programs in the U.S. demand worldly unmatched systems efforts, their "spin-off" contribution in the field of systems technology and engineering tends to be considerable.

Because of the U.S. superpower position in military technology, the generalization of the U.S. experience to other countries should be cautioned. On the whole, however, it seems not pragmatic for most other countries to expect significant contribution from "spin-off." As to the other military superpower--the USSR, its "spin-off" has been either "distorted" or stymied for lack of a strong, market-oriented civilian industry.

Notes

[1] Freeman (1982), p. 191 and Nelson (1990), p. 125.

[2] Smith (1990), p. 133.

[3] DOD's technology base programs include research (category 6.1), exploratory development (category 6.2), and advanced exploratory development (category 6.3A).

[4] For DOD's budget, see U.S. OTA (1989), p. 20.

[5] The laws promoting technology transfer from Federally sponsored programs include the Stevenson-Wydler Technology Innovation Act of 1980, the Patent and Trademark Amendments Act of 1980, the Bayh-Dole Patent Amendments of 1984, the Federal Technology Transfer Act of 1986, the Omnibus Trade and Competitiveness Act of 1988, and the National Competitiveness Technology Transfer Act of 1989.

[6] 10 standards used to evaluate the effects of defense R&D spending are discussed in Carter (1989), pp. 4-6.

[7] For the impacts of information technology on "technological paradigm," see Dosi (1982).

[8] For the impacts of information technology on "technology system" and "techno-economic paradigm," see Freeman and Perez (1986).

[9] Burnett and Scherer (1990), pp. 294-295.

[10] In both 1971 and 1981, the categories of aircraft/missiles and electrical equipment (including communications equipment and electronic components) respectively accounted for about half and about a quarter to a third of Federal military R&D funding. See Rosenberg (1986), pp. 11-12.

[11] Braun and Macdonald (1982), p. 98.

[12] The rapid diffusion of transistor technology is partly due to AT&T's consent to license its patents and to refrain from open market competition as part of an antitrust settlement in the mid-1950s.

[13] Misa (1987).

[14] Schnee (1978), pp. 15-16.

[15] Braun and Macdonald (1978), pp. 59-63, and Schnee (1978), pp. 11-13.

[16] Phillips (1982), pp. 162-179.

[17] Schnee (1978), pp. 10-11.

[18] Flamm (1987), pp. 65-70 and 108-110.

[19] Flamm (1987), pp. 78-80.

[20] U.S. OTA (1990), p. 188, and Flamm (1987), pp. 81-82.

[21] Schnee (1978), pp. 13-14.

[22] Thompson (1984).

[23] For a brief discussion of the U.S. commercial aircraft industry, see Dertouzos et al. (1989), pp. 201-216.

[24] Donald (1987), p. 14.

[25] Langford (1987), p. 37.

[26] For the government's influence on the U.S. commercial aircraft industry, see Mowery and Rosenberg (1982).

[27] Rosenberg (1986), pp. 24-26.

[28] Rosenberg (1986), p. 24.

[29] For a brief review of the development of jet engine, see White (1984), pp. 10-18.

[30] Dertouzos et al. (1989), p. 206.

[31] U.S. OTA (1989), pp. 170-171.

[32] U.S. OTA (1988), p. 1.

[33] For a brief review of this history, see Chiang (1991).

[34] Flamm (1987), pp. 48-49.

[35] Flamm (1987), pp. 121-122.

[36] Flamm (1987), p. 76.

[37] Flamm (1987), pp. 121-123.

[38] Flamm (1987), pp. 59-61.

[39] Flamm (1987), pp. 75-76, and U.S. OTA (1989), pp. 169-170 and 173-174.

[40] For the Polaris program, see Sapolsky (1972). For a brief review of the history of PERT, see Moder et al. (1983), pp. 10-14.

[41] Schnee (1977).

[42] Rosenberg (1986), p. 27.

[43] Dertouzos et al. (1989), p. 206.

[44] There are many reports about Concorde. See, for example, Feldman (1985). For the U.S. Supersonic Transports Program, see Horwitch (1982).

[45] For a brief discussion of the National Aerospace Program, see Korthals-Altes (1987).

[46] U.S. OTA (1989), pp. 169-170 and 173-174.

[47] Donald (1987), pp. 38, 44 and 62.

[48] Burnett and Scherer (1990), pp. 295-300.

49 For a brief discussion of the technical issues of the C-5A transport, see Seamans (1972), pp. 2-4.

50 For the military contracting behavior and the Lockheed case, see Burnett and Scherer (1990), pp. 300-305.

51 For the development of NC and the "distortion" of commercial efforts, see Noble (1984).

52 U.S. OTA (1989), pp. 167-168.

53 For a comparison of advanced materials technology strategies in the U.S. and Japan, see U.S. OTA (1988).

54 Misa (1987).

55 Thompson (1984), pp. 68-73.

56 Braun and Macdonald (1982), p. 70.

57 Braun and Macdonald (1982), p. 80.

58 Braun and Macdonald (1982), p. 98.

59 Dallmeyer (1987), p. 48.

60 DeGrasse (1983), pp. 84-96.

61 For VHSIC Program, see Yoshino and Fong (1985).

62 Statistics from Dataquest.

63 Schnee (1978), p. 9.

64 Flamm (1987), p. 108.

65 Flamm (1987), pp. 97-99.

66 Thompson (1984), pp. 68-72.

67 U.S. OTA (1990), pp. 33-35 and 161-163.

68 Nelson (1990).

69 For the development history of aircraft, including the supersonic transports, in the USSR, see Moon (1989).

70 For a brief discussion of nuclear power, information technology and some other technologies in the USSR, see Chiang (1990).

Bibliography

Braun, Ernest and Macdonald, Stuart (1982), *Revolution in Miniature*, U.K.: Cambridge University Press.

Burnett, William B. and Scherer, Frederic M. (1990), The Weapons Industry, in Adams, Walter (ed.), *The Structure of American Industry*, New York, NY: Macmillan Publishing Company.

Carter, Ashton B. (1989), Analyzing the Dual Use Technologies Question, a paper presented to the Workshop on "Military and Civilian Technologies: A Changing Relationship" in Harvard University Kennedy School of Government, Cambridge, MA, November 1.

Chiang, Jong-Tsong (1990), Management of Technology in Centrally Planned Economies, *Technology in Society*, 12/4.

Chiang, Jong-Tsong (1991), The Potential of "Spin-off" from A Systems Perspective, *Technology in Society*, 13/2 (forthcoming).

Dallmeyer, Dorinda G. (1987), National Security and the Semiconductor Industry, *Technology Review*, November-December:47-55.

DeGrasse, Robert W., Jr. (1983), *Military Expansion Economic Decline*, Armonk, NY: M.E. Sharpe.

Dertouzos, M.L., Lester, R.K. and Solow, R.M. (1989), *Made in America: Regaining the Productive Edge*, Cambridge, MA: The MIT Press.

Donald, David (1987), *Aircraft of the United States Air Force*, London: Aerospace Publishing.

Dosi, Giovanni (1982), Technological Paradigms and Technological Trajectories, *Research Policy*, 11:147-162.

Feldman, E.J. (1985), *Concorde and Dissent: Explaining High Technology Failures in Britain and France*, U.K.: Cambridge University Press.

Flamm, Kenneth (1987), *Targeting the Computer: Government Support and International Competition*, Washington, D.C.: The Brookings Institution.

Freeman, Christopher (1982), *The Economics of Industrial Innovation*, Cambridge, MA: The MIT Press.

Freeman, Christopher and Perez, Carlota (1986), The Diffusion of Technical Innovation and Changes of "Techno-Economic Paradigm," paper presented at Conference on "Diffusion of Innovations" in DAEST, Venice, Italy, March.

Horwitch, Mel (1982), *Clipped Wings*, Cambridge, MA: The MIT Press.

Korthals-Altes, Stephen W. (1987), Will the Aerospace Plane Work? *Technology Review*, January:43-51.

Langford, John S., III (1987), Federal Investment in Aeronautical Research and Development: Analyzing the NASA Experience, MIT Doctoral Thesis, Cambridge, MA.

Misa, Thomas J. (1985), Military Needs, Commercial Realities, and the Development of the Transistor, 1948-1958, in Smith, Merritt Roe (ed.), *Military Enterprise and Technological Change*, Cambridge, MA: The MIT Press.

Moder, J.J., Phillips, C.R. and Davis, E.W. (1983), *Project Management with CPM, PERT and Precedence Diagramming*, New York, NY: Van Nostrand Reinhold.

Moon, Howard (1989), *Soviet SST: the Technopolitics of the Tupolev-144*, New York, NY: Orion Books.

Mowery, David C. and Rosenberg, Nathan (1982), The Commercial Aircraft Industry, in Nelson, Richard R. (ed.), *Government and Technical Progress: A Cross-Industry Analysis*, Elmsford, NY: Pergamon Press.

Nelson, Richard R. (1990), U.S. Technological Leadership: Where Did It Come from and Where Did It Go? *Research Policy*, 19:117-132.

Noble, David (1984), *Forces of Production*, New York, NY: Alfred Knopf.

Phillips, Almarin (1982), The Computer Industry, in Nelson, Richard R. (ed.), *Government and Technical Progress: A Cross-Industry Analysis*, Elmsford, NY: Pergamon Press.

Rosenberg, Nathan (1986), Civilian "Spillovers" from Military R&D Spending: The American Experience since World War II, paper presented at the Conference on "Technical Cooperation and International Competitiveness," Lucca, Italy, April 2-4.

Sapolsky, Harvey M. (1972), *The Polaris System Development*, Cambridge, MA: Harvard University Press.

Schnee, Jerome R. (1977), Space Program Impacts Revisited, *California Management Review*, 20/1:62-73.

Schnee, Jerome R. (1978), Governmental Influence on Innovation, *Research Policy*, January:2-24.

Seamans, Robert C., Jr. (1972), Lessons Learned and Future Directions in the Management of Technical Programs, lecture presented in the von Karman Lecture of the Advisory Group for Aerospace Research and Development, NATO, Brussels, Belgium, September.

Smith, Bruce L.R. (1990), *American Science Policy since World War II*, Washington, D.C.: The Brookings Institution.

Smith, Merritt Roe (1987), Army Ordnance and the "American System" of Manufacturing, 1815-1861, in Smith, Merritt Roe (ed.), *Military Enterprise and Technological Change*, Cambridge, MA: The MIT Press.

Thompson, Gordon (1984), The Genesis of Nuclear Power, in Tirman, John (ed.), *The Militarization of High Technology*, Cambridge, MA: Ballinger.

U.S. OTA (1988), *Advanced Materials by Design (Summary)*, Washington, D.C.: Government Printing Office.

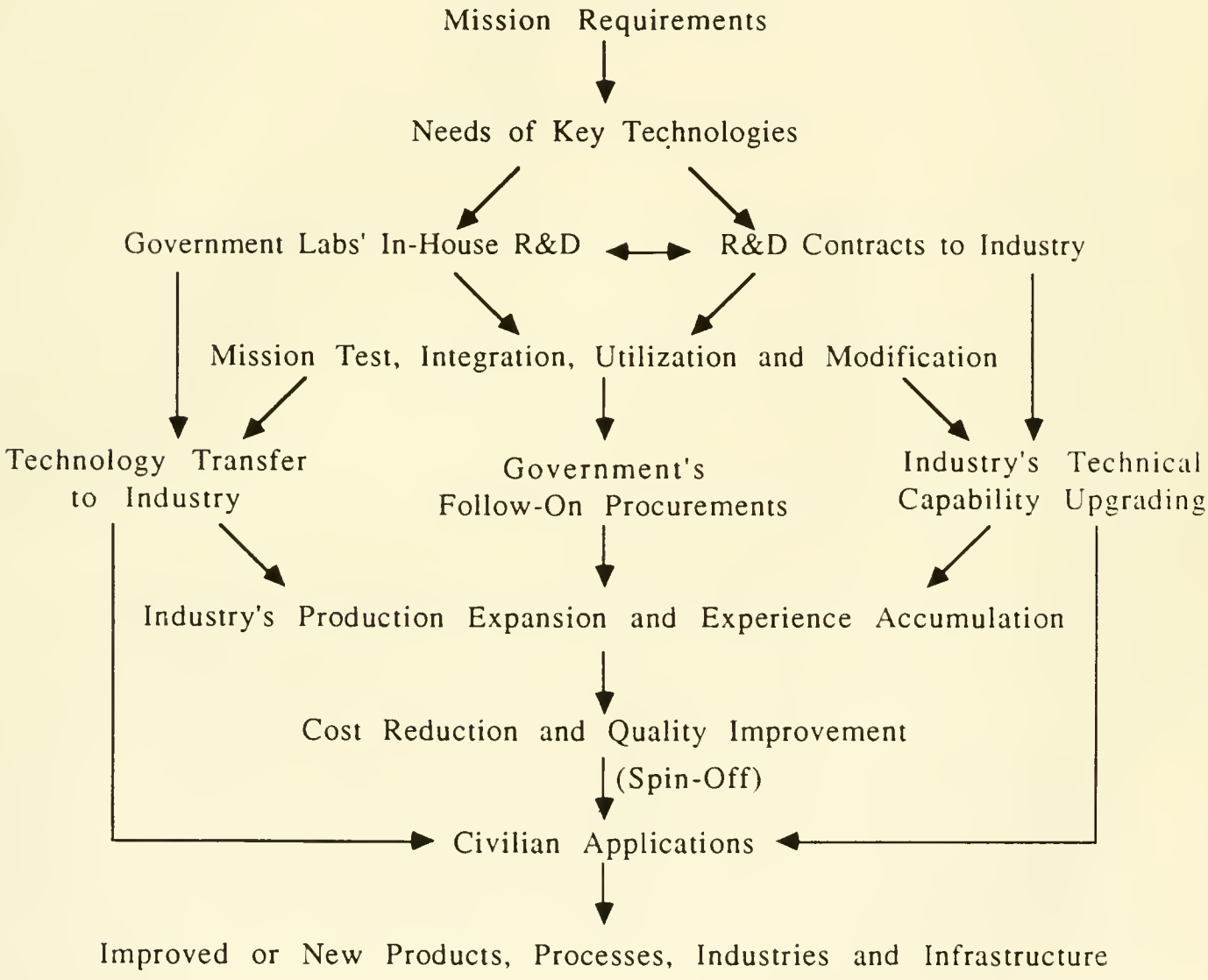
U.S. OTA (1989), *Holding the Edge: Maintaining the Defense Technology Base*, Washington, D.C.: Government Printing Office.

U.S. OTA (1990), *Making Things Better: Competing in Manufacturing*, Washington, D.C.: Government Printing Office.

White, George R. (1984), Technology in the Aircraft Industry, unpublished manuscript, Cambridge, MA: Harvard Business School.

Yoshino, Michael Y. and Fong, Glenn R. (1985), The Very High Speed Integrated Circuit Program: Lessons for Industrial Policy, in Scott, Bruce and Lodge, George (eds.), *U.S. Competitiveness in the World Economy*, Boston, MA: Harvard Business School Press.

Exhibit 1. "Spin-Off" from Mission-Oriented Technology Programs



Date Due

JAN 07 1992

MAR 06 1992

DEC. 03 1992

Lib-26-67

MIT LIBRARIES

3 9080 00666020 0